Clustering around the radio-galaxy MRC0316-257 at z=3.14

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ABSTRACT

We report here the spectroscopic identification of galaxies in the neighborhood of the radio-galaxy MRC0316-257, at a redshift $z \sim 3.14$. Candidate cluster galaxies were selected from deep V and I images combined with narrow band imaging at the wavelength of redshifted Lyα. Follow-up multi-slit spectroscopy has allowed confirmation of the redshift of the radio-galaxy, $z = 3.1420 \pm 0.0020$, and identification of two associated galaxies at redshifts $z = 3.1378 \pm 0.0028$ and $z = 3.1351 \pm 0.0028$ respectively. The first galaxy is 0.3 h_{50}^{-1} Mpc from the radio-galaxy, is resolved with an intrinsic size $11.6 \pm h_{50}^{-1}$ kpc, and shows $Ly\alpha$ in emission with rest $W_{Ly\alpha} = 55 \pm 14$Å. In addition, its extremely blue $V - I$ color might possibly indicate a proto-galaxy forming a first generation of stars in a low dust medium. The second galaxy is 1.3 h_{50}^{-1} Mpc away from the radio-galaxy, is marginally resolved and, in addition to Lyα in emission, shows CIV in emission with a broad component indicating the contribution from an AGN. The comoving density of galaxies with $V < 23.8$ and a $Ly\alpha$ flux $> 10^{-16}$ ergcm^{-2}sec^{-1} in the vicinity of MRC0316-257 is $\sim 2.5 \times 10^{-3} h_{50}^3 Mpc^{-3}$, significantly higher than the expected background density of field galaxies with similar properties, and might indicate a rich cluster or proto-cluster environment. These observations indicate that the environment of high redshift radio-galaxies may provide significant numbers of galaxies from which to study the early stages of cluster formation and galaxy evolution.

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Subject headings: cosmology: observations – cosmology: large scale structure of universe – galaxies: clusters: general – galaxies: formation – galaxies: evolution

1. Introduction

The evolution of clusters of galaxies has important implications to our knowledge of the fundamental cosmological parameters. As they are the most massive gravitationally bound systems in the universe, the evolution of clusters is highly sensitive to the physics of cosmic structure formation and the values of the fundamental cosmological parameters. Moreover, clusters are valuable laboratories to study the evolution of many galaxies at a common redshift.

Although a number of galaxies with luminosities $\sim L^*$ are now observed out to redshifts $\sim 3 - 4$ (Steidel et al. 1996, Fontana et al. 1996), very few candidate clusters of galaxies have been spectroscopically confirmed at redshifts near or above unity (Giavalisco et al. 1994, Le Fèvre et al. 1994a, Dickinson 1995, Pascarelle et al. 1996, Francis et al. 1996). At these very high redshifts, the prevalence of clusters, proto-clusters, or other large scale structures in the galaxy distribution is as yet unknown, and the evolution of large scale structures may well be at a critical stage (Peebles et al. 1989, Evrard&Charlot 1994, Frenk et al. 1996), where observations can directly constrain cosmological models.

At intermediate redshifts, powerful radio-galaxies are frequently located in rich clusters (Yee&Green 1984, Hill&Lilly 1991, Dickinson 1994), therefore, a possible search strategy is to look for clusters around known powerful radio-galaxies. As part of a program to identify clusters and study their properties at redshifts larger than $z \sim 0.8$, we report here the discovery of galaxies within $\sim 1h_{50}^{-1}$ Mpc and 1000 kms^{-1} from the 1Jy radio galaxy MRC0316-257 (McCarthy et al. 1990), at $z = 3.14$.

$H_0 = 50$ kms^{-1}Mpc^{-1} and $q_0 = 0.5$ are used throughout this letter.

2. Observations

We have observed a $9.2' \times 8.5'$ field around MRC0316-257 with the Multi Object imaging Spectrograph (MOS) at CFHT (Le Fèvre et al. 1994b). Deep broad band V and I images as well as narrow band images in a filter with central wavelength 5007Å and bandwidth 96Å, containing the $Ly\alpha$ line redshifted to $z \sim 3.14$, were obtained the night of

20 December 1995. Several images were obtained for each filter, after small telescope offsets were performed, to improve the flat fielding accuracy. Total integration times were 2700, 1200, 5100 seconds in V, I and the 5007Å filters, respectively. Standard image processing was performed the next day, and the V and 5007Å images were blinked visually to provide a list of cluster candidates for subsequent multi-slit spectroscopy during the nights 21-24 December 1995. The narrow band 5007Å images can be expected to identify galaxies with $Ly\alpha$ in a redshift range $z = 3.081 - 3.160$, foreground galaxies with [OII]3727Å in emission with a redshift $z = 0.330 - 0.356$, or the rarer occurence of galaxies with [OIII]5007Å with $z \sim 0$.

The narrow band image is compared to the V band image of the MRC0316-257 field in Figure 1 (plate 1). Two galaxies exhibit strong excess emission in the narrow band filter, and were subsequently observed spectroscopically, together with more marginal candidates. Multi-slit masks were prepared with the highest priority given to the cluster candidates as defined above, and other slits were placed on galaxies brighter than $V \sim 23.8$ when no other candidate was available. The observations of about 30 galaxies per mask were performed with the O300 grism, with 300 l/mm and peak transmission at ∼5900Å, and slits 1.75″ wide, providing a spectral range of 4500-9000Å and a resolution of 20Å. Three masks have received cummulated exposure times of 19800, 8700, and 8700 seconds. Data reduction of the spectra in the first mask obtained the night of 21 December 1995 was performed the following afternoon, and confirmed that these candidate galaxies had emission lines at ∼5030Å. These galaxies were subsequently reobserved in the following multi-slit mask for a total exposure time of 28500 sec.

Final data reduction was performed with the MULTIRED package implemented under IRAF, and redshifts were measured and assigned classes as described in Le Fèvre et al. (1995). The two galaxies common to 2 different masks were treated separately by averaging the flat-fielded and sky corrected 2D spectra obtained from each 2 mask. The 3σ detection limit in the shortest integration spectra is $\sim 1.5 \times 10^{-18}$ ergcm^{-2}sec^{-1}Å^{-1} around 5000Å, and our spectra would have allowed us to identify any emission line with a flux larger than 3×10^{-17} ergcm^{-2}sec^{-1}. A total of 51 galaxies have secure redshift measurements in the range $0 \leq z \leq 1.3$; 2 stars were identified, and we failed to measure redshifts for 45 galaxies.

3. Results

McCarthy et al. (1990) noted that $Ly\alpha$ was the only feature in support of their redshift for MRC0316-257, while Eales et al. (1993) identified [OIII]5007 from IR spectroscopy. Our spectra confirm $Ly\alpha$ in emission, as well as CIV1549Å, HeII1640Å and CIII]1909Å (figure

1). The redshift of the radio-galaxy MRC0316-257 is therefore $z = 3.1420 \pm 0.0020$. The V image shows another galaxy of roughly equal magnitude 2.7 arcseconds away, while in the 5007Å image the eastern galaxy disappears almost completely.

In addition to the radio-galaxy, we have identified spectroscopically two galaxies with a redshift similar to the radio-galaxy. The first one, "galaxy A", is 44 arcseconds away from the radio-galaxy. Its spectrum shows a strong line at 5030.3Å, and faint features with marginal S/N at the same redshift (fig.2). A cross–correlation of the spectrum of galaxy A, after subtraction of the 5030Å emission line, with a template spectrum with line widths taken from Yee et al. (1996), gives a marginal correlation at z=3.14 with a correlation coefficient R=2.8. The observed equivalent width of the emission line is 230±60Å, which, if it was [OII]3727Å at z=0.350, would indicate a rest frame $W_{OII} = 170 \pm 44$Å, larger than any equivalent width for galaxies in the Canada-France Redshift Survey (CFRS), or 3 times larger than for any galaxies at $z \leq 0.4$ in the CFRS (Hammer & al. 1996). Moreover, all galaxies in the CFRS with rest $W_{OII} > 30$Å have rest $W_{OIII} > 5$Å and $W_{H\alpha} > 40$Å, which would have been easily identified in our spectra at a redshift $z = 0.349$. The identification of the line at 5030Å with $Ly\alpha$ at $z = 3.1378 \pm 0.0028$ seems therefore to be secure.

The second galaxy, "galaxy B", is located 182 arcseconds from MRC0316-257. Its spectrum shows $Ly\alpha$ and CIV1549Å, and therefore gives a secure redshift $z = 3.1351 \pm 0.0028$. Both CIV1549Å, and to a lesser extent $Ly\alpha$ exhibit a broad component, which indicates the presence of an AGN.

Close examination of the images indicate that both MRC0316-257 and "galaxy A" are resolved under FWHM=1.5 arcseconds seeing, while "galaxy B" is only marginally resolved. After deconvolution from the observed PSF, the half-light radii of MRC0316-257 and "galaxy A", are 8.9 ± 2.0 and 11.6 ± 1.1 h^{-1} kpc respectively. The fact that galaxy B is quite compact supports the contribution of an AGN. The V, I and $Ly\alpha$ images of galaxy A are strinkingly different: the peaks of continuum V and line emission are offset by 0.6 arcsec, with the peak of $Ly\alpha$ emission extending toward the SW, where little or no continuum light is detected in the V and I bands, and little or no emission is observed in I at the peak of $Ly\alpha$ emission, while several blobs of emission appear 3 arcseconds to the NW in the I band.

4. Discussion

In figure 3 we plot the (V−I) vs (V−5007Å) color-color diagram. Besides MRC0316-257, and the two associated galaxies identified in spectroscopy, two galaxies have significant

excess emission in the 5007Å filter (V−5007> −1.2). One of these galaxies has a redshift $z = 0.335$, and the excess emission in the 5007Å filter is coming from the [OII]3727Å emission line. The other galaxy, galaxy C, has not been observed spectroscopically. Therefore, in our imaging field of view of 78.2 arcmin^2, we have three confirmed galaxies at $z \sim 3.14$, above our detection thresholds of $W_{Ly\alpha} > 12$Å and $V < 23.8$, and a fourth galaxy, galaxy C, which remains a good but unconfirmed candidate galaxy at $z \sim 3.14$.

Any estimate of the space density of $z \approx 3.14$ galaxies from our observations is necessarily quite uncertain due to the small number of objects which we detect. The maximum redshift depth probed is set by the range over which our narrow band filter would detect the Lyα emission line, i.e. $3.081 < z < 3.160$. Under that assumption, the resulting co-moving cosmological volume surveyed is therefore $13900 h_{50}^{-3}$Mpc^3 assuming $q_0 = 0.5$. (For $q_0 = 0$, the effective volumes are 7.4× larger, and the densities correspondingly smaller.) However, the three galaxies which we have confirmed spectroscopically are confined to a much smaller redshift range, close to the radio galaxy: $3.1351 < z < 3.1420$. This corresponds to a rest–frame velocity difference $\Delta v = 500$km s^{-1}, quite in line with expectations for galaxy clusters and/or "walls" of large–scale struture. It is therefore likely that the effective "cluster" volume is much smaller than the value given above. Assuming $\Delta z = 0.0069$, the corresponding co-moving volume would then be $1210 h_{50}^{-3}$Mpc^3. We therefore may bracket the range of possible space densities by assuming $3/13900 < n$ (Mpc^{-3}) $< 4/1210$, or $2.2 \times 10^{-4} < n(h_{50}^3\mathrm{Mpc}^{-3}) < 3.3 \times 10^{-3}$, with a "best guess" value of $3/1210 = 2.5 \times 10^{-3} h_{50}^3$Mpc^{-3}.

The population of $3.0 < z < 3.5$ field galaxies identified by Steidel *et al.* 1996 has a comoving space density of $3.6 \times 10^{-4} h_{50}^3$Mpc^{-3} for q_0=0.5. At face value, this would imply that our "best guess" space density represents an overdensity of $\sim 7\times$ compared to the field population at similar redshift. However, it is difficult to make a direct comparison between our "cluster" space density and the"field" value since our galaxies were selected on the basis of strong Lyα flux, and have brighter continuum magnitudes ($V < 23.8$) than the Steidel *et al.* objects (which have $\mathcal{R} < 25.5$). Therefore the estimate given above for the cluster overdensity is almost certainly a substantial *underestimate.* Even our derived lower limit of $n > 2.2 \times 10^{-4} h_{50}^3$Mpc^{-3} for the 0316-257 field is substantially higher than the corresponding space density of field galaxies sharing the same continuum magnitudes and Lyα properties.

The rest frame $Ly\alpha$ equivalent widths are 500 ± 150, 55 ± 14, 110 ± 18Å, for the radio galaxy, and galaxies A and B respectively. While the radio-galaxy and galaxy B have resolved $Ly\alpha$, with $FWHM = 30 \pm 3$Å and 22 ± 4Å respectively, and CIV is resolved for galaxy B, with $FWHM(CIV) = 38 \pm 8$Å after deconvolution by the instrumental response,

$Ly\alpha$ is unresolved at our resolution for galaxy A. This may indicate that $Ly\alpha$ in galaxy A is produced mainly by stellar photo-ionisation. Even after correcting for the contribution of the Lyman alpha line to the V band, Galaxy A is extremely blue, with $V - I < -0.5$. This is very unusual for faint galaxies, and indeed Galaxy A is by far the bluest object in our field of view, as can be seen from figure 3. Galaxy A is bluer than most or all of the z∼3 objects reported by Steidel et al. (1996). It is also interesting that its Lyman alpha emission is significantly stronger than that in most of the Steidel et al. Lyman break galaxies. The blue color and strong Ly-a emission may indicate an object dominated by OB-stars in a strong starburst with very little dust. The complex morphology of galaxy A is quite different from the morphology of galaxies identified on the basis of the 912Å discontinuity (Steidel et al. 1996, Giavalisco et al. 1996), with complex spatial distribution of continuum and line emission as described in section 3. While the evidence for old stars will have to be searched for at redder wavelength, this galaxy might well be forming its first stars and fit the definition of a proto-galaxy.

5. Conclusion

We have spectroscopically identified 2 galaxies at the same redshift as the radio-galaxy MRC0316-257, z∼ 3.14. These galaxies exhibit $Ly\alpha$ in emission with $W(Ly\alpha) > 50$Å. One galaxy is resolved with a size $11h^{-1}$ Mpc, has unresolved $Ly\alpha$, and extremely blue $V - I$ color, which might indicate that the main photo-ionising process is coming from a first generation of young stars in a low dust medium. The other galaxy is unresolved, and has broad $Ly\alpha$ and CIV emission lines, indicating the presence of an AGN.

These observations of galaxies around MRC0316-257 provide tentative evidence for a region of high galaxy density, possibly indicative of clustering of galaxies occuring at $z = 3.14$. They indicate that the search for galaxies around very high redshift radio-galaxies is indeed possible from $Ly\alpha$ imaging techniques. However, the total number of galaxies identified with an observed $Ly\alpha$ luminosity $> 10^{-16}$ ergcm^{-2}sec^{-1} is small, indicating the limits of this technique, in agreement with previous searches. Lyman break techniques, as successfuly applied by Steidel et al. (1996), will be required to identify additional galaxies at the same redshift and confirm the existence of a cluster or proto-cluster of galaxies.

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Table 1. Properties of the galaxies at z≃3.14

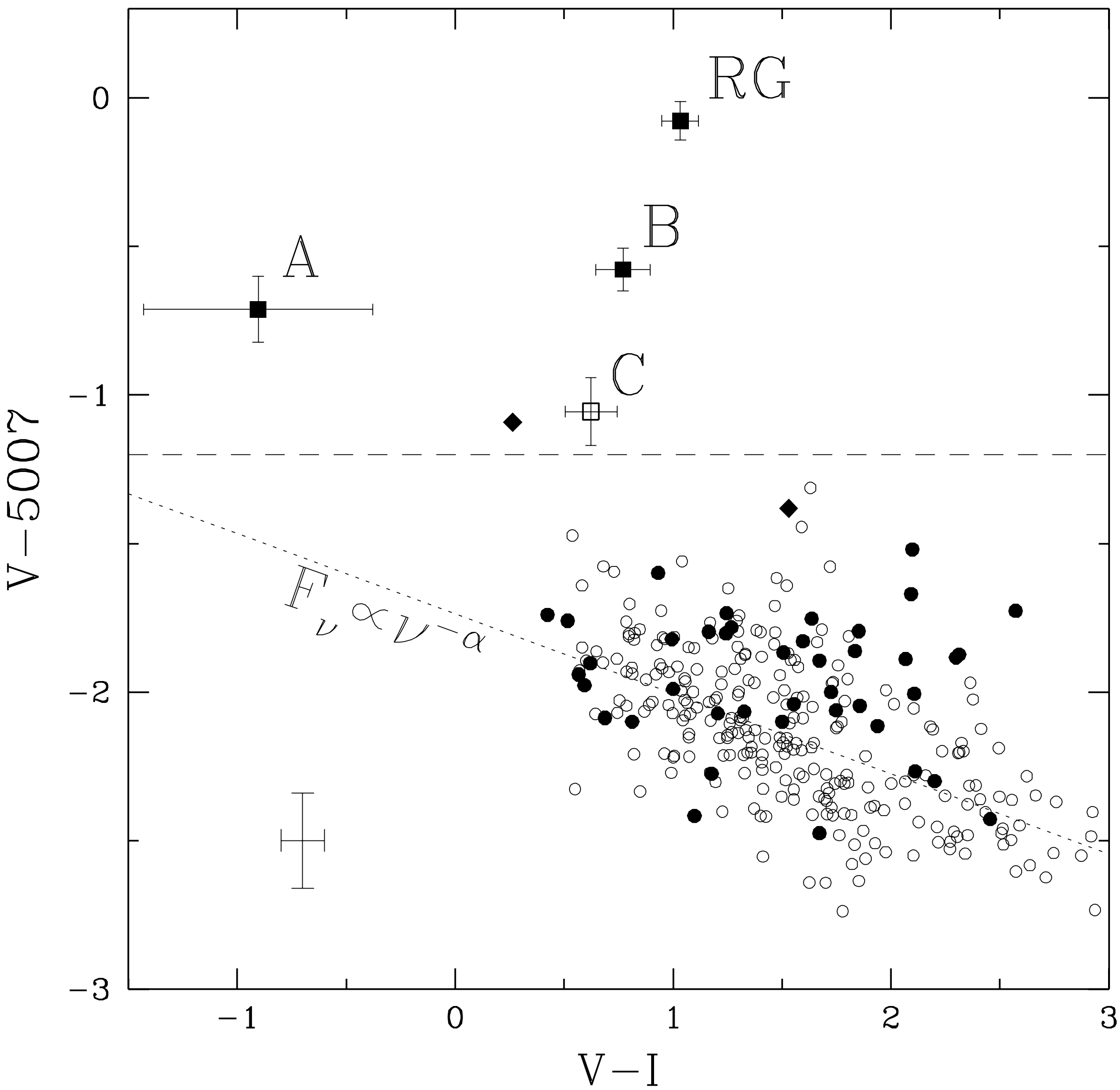
Object	α_{1950}	δ_{1950}	$f_{Ly\alpha}$ (ergs^{-1}cm^{-2})	V	I	$M_B^{(a,b)}$	FWHM (kpc)$^{(a)}$
0316-257	$03^h16^m02.^s66$ $^{(c)}$	$-25°46'04''$ $^{(c)}$	3.3±0.1 10^{-16}	23.24±0.04	22.53±0.06	−23.27	8.9±2.0
A	$03^h15^m59.^s62$	$-25°45'52''$	1±0.1 10^{-16}	23.84±0.04	24.97±0.30	−22.67	11.6±1.1
B	$03^h15^m50.^s32$	$-25°44'53''$	2.3±0.2 10^{-16}	23.21±0.03	22.67±0.09	−23.30	2.3 $^{(d)}$
C $^{(e)}$	$03^h15^m51.^s92$	$-25°42'38''$	0.5 10^{-16} $^{(f)}$	23.87±0.06	23.48±0.10	−22.64	6.3±0.9

Note. — $^{(a)}$ Assuming $H_0 = 50$ kms^{-1}Mpc^{-1} and $q_0 = 0.5$
$^{(b)}$ The K-correction has been estimated from Bruzual 1983
$^{(c)}$ From McCarthy et al. 1990
$^{(d)}$ Unresolved
$^{(e)}$ Candidate z=3.14 galaxy on the basis of narrow band imaging only
$^{(f)}$ Estimated from narrow band imaging

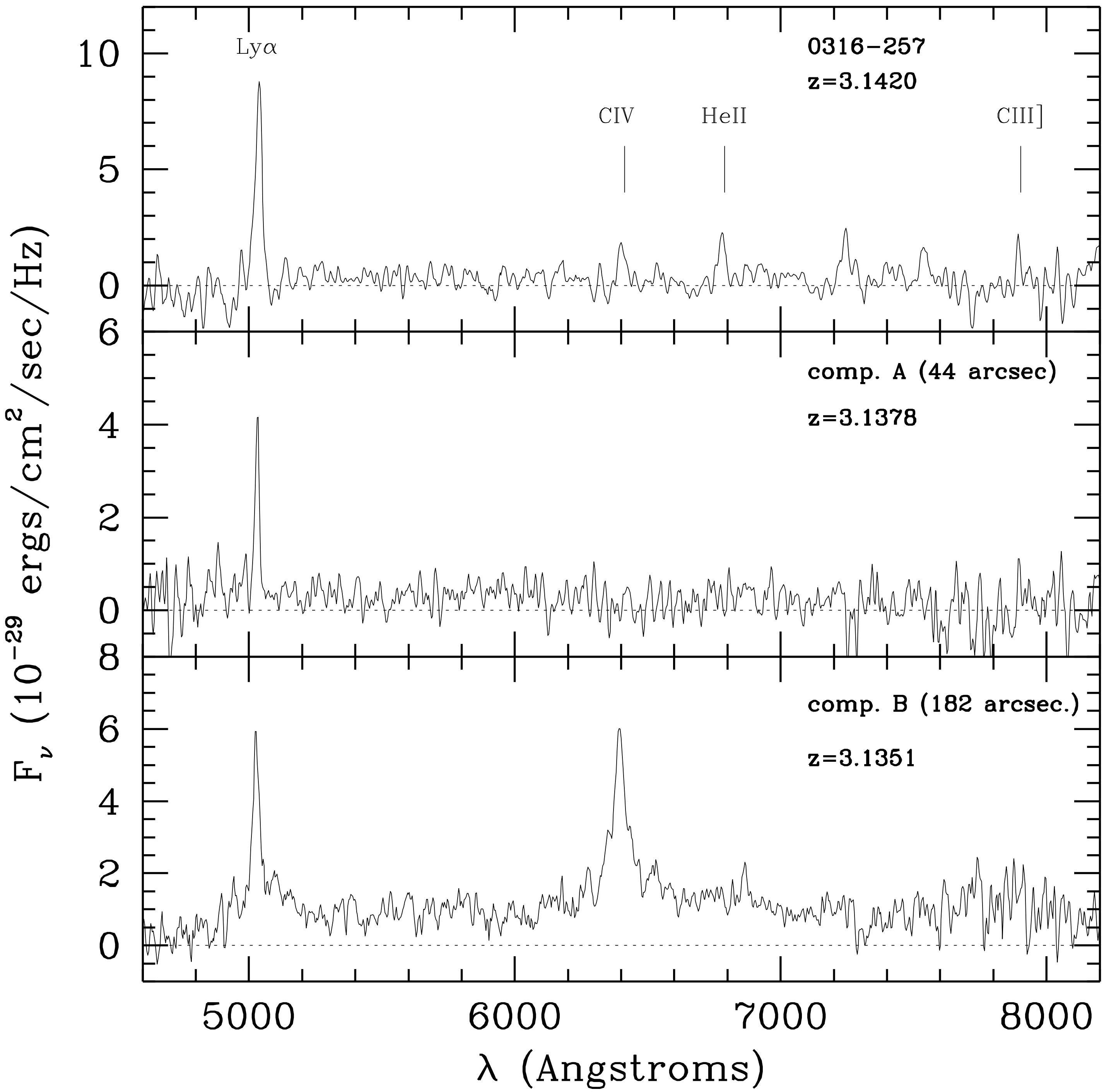
Fig. 1.— V image *(top)* and 5007Å image *(bottom)* of a field $2'.15 \times 4'.$ around the radio-galaxy MRC0316-257 (RG). North is at the top, East to the left. Galaxies A and B clearly exhibit excess emission in the 5007Å filter, which contains Lyα redshifted to $z \sim 3.14$.

Fig. 2.— CFHT spectra: radio-galaxy MRC0316-257 *(top)*, galaxy A *(middle)*, galaxy B *(bottom)*

Fig. 3.— (V−I) vs. (V−5007Å) diagram. Solid symbols indicate spectroscopically observed galaxies: squares for $z \sim 3.14$ galaxies, diamonds for the galaxies with $z \sim 0.35$, circles for other galaxies with measured redshift. Open symbols indicate galaxies not observed spectroscopically: square for a galaxy with V−5007Å> -1.2, a good candidate $z \sim 3.14$ galaxy, circle for other galaxies. Note that the V-I for galaxy A is $V - I = -0.7$ after correction for the $Ly\alpha$ line contamination in the filter bandpass, still extremely blue.



RG
B
A
C
$F_\nu \propto \nu^{-\alpha}$
V−5007
V−I
0
−1
−2
−3
1
2
3



Lyα
0316-257
z=3.1420
CIV
HeII
CIII]
comp. A (44 arcsec)
z=3.1378
comp. B (182 arcsec.)
z=3.1351
F_ν (10^{-29} ergs/cm^2/sec/Hz)
λ (Angstroms)